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(54) **SEISMIC NAVIGATION**

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(22) Filed: **Jul. 31, 2012**

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(51) **Int. Cl.**

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E21B 47/022 (2012.01)

(52) **U.S. Cl.**

CPC ***E21B 47/02208*** (2013.01)

(58) **Field of Classification Search**

CPC . E21B 47/02208; E21B 47/091; E21B 46/09; E21B 47/024

See application file for complete search history.

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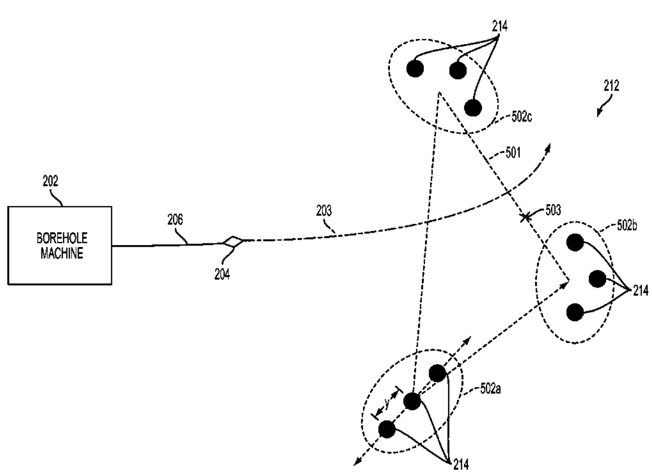
(57) **ABSTRACT**

A sensor array system includes a sensor array comprising a first sensor disposed underground and a second sensor disposed underground, and a processor communicatively coupled to the sensors of the sensor array, the processor operative to receive signals from the sensors of the sensor array indicative of seismic activity, and identify a position of a portion of a borehole machine operative to induce the seismic activity while disposed in an underground borehole.

13 Claims, 7 Drawing Sheets



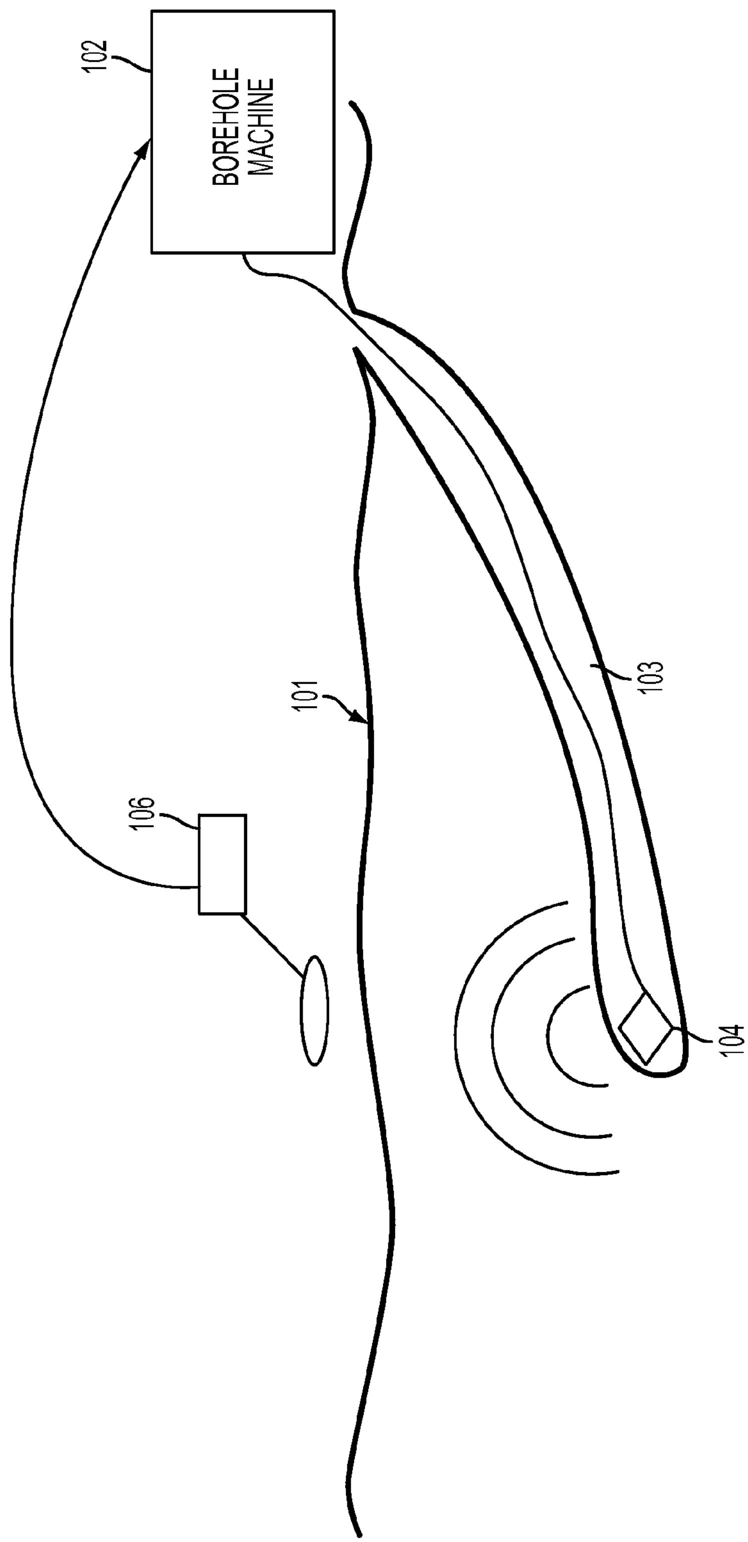


FIG. 1
PRIOR ART

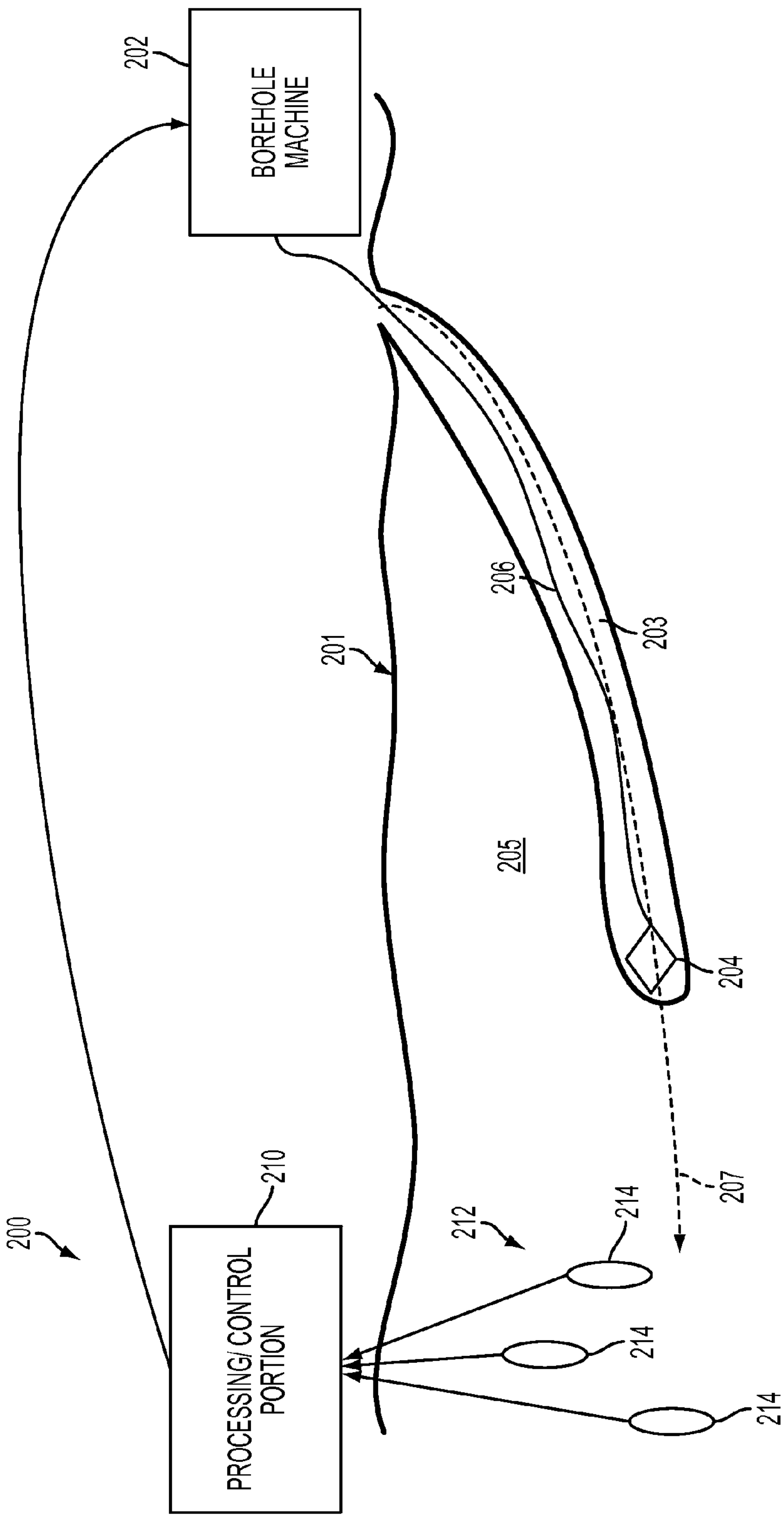

BOREHOLE MACHINE
202
201
206
203
205
204
207
200
210
212
214
214
214
PROCESSING/ CONTROL PORTION

FIG. 2

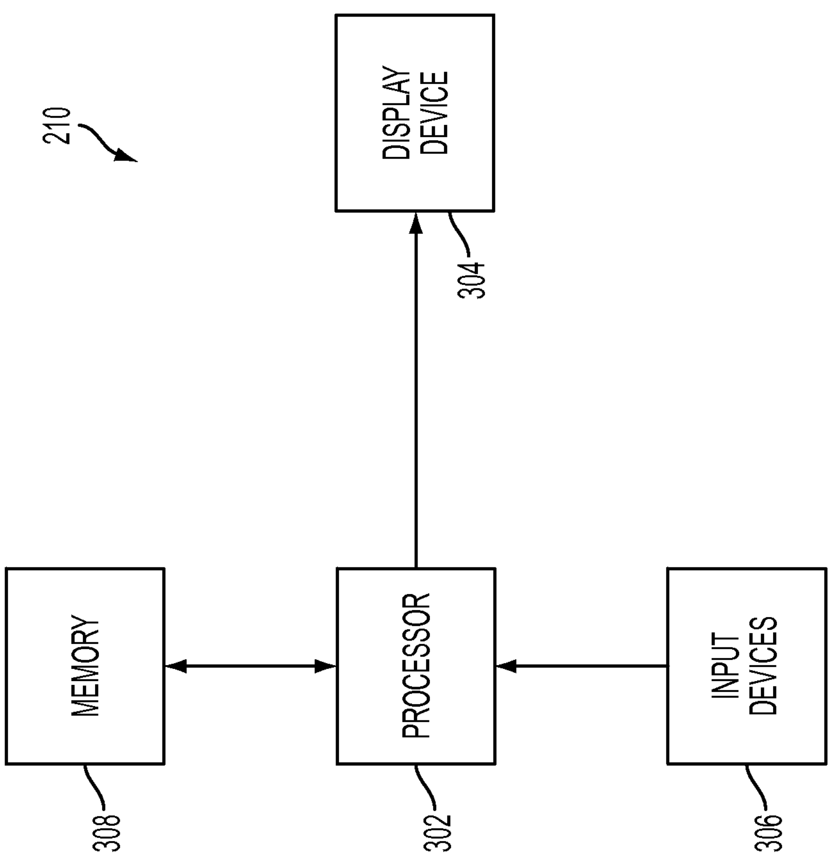

210
DISPLAY DEVICE
304
MEMORY
PROCESSOR
INPUT DEVICES
308
302
306

FIG. 3

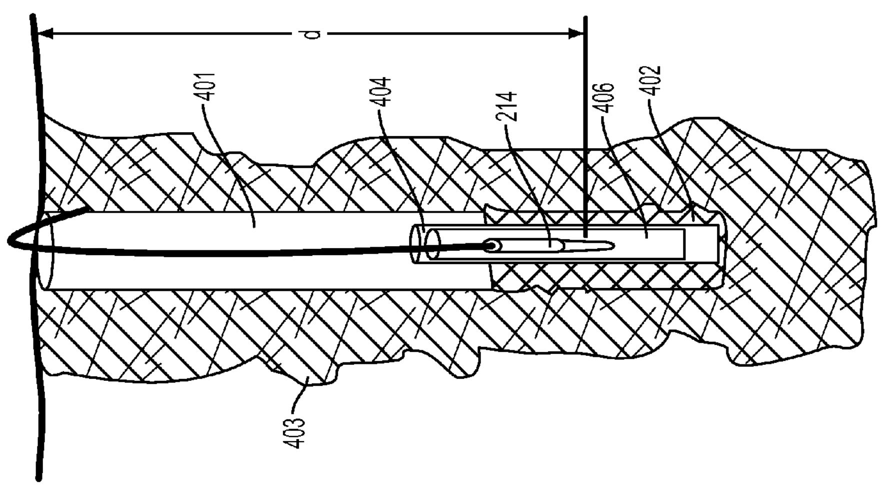


FIG. 4

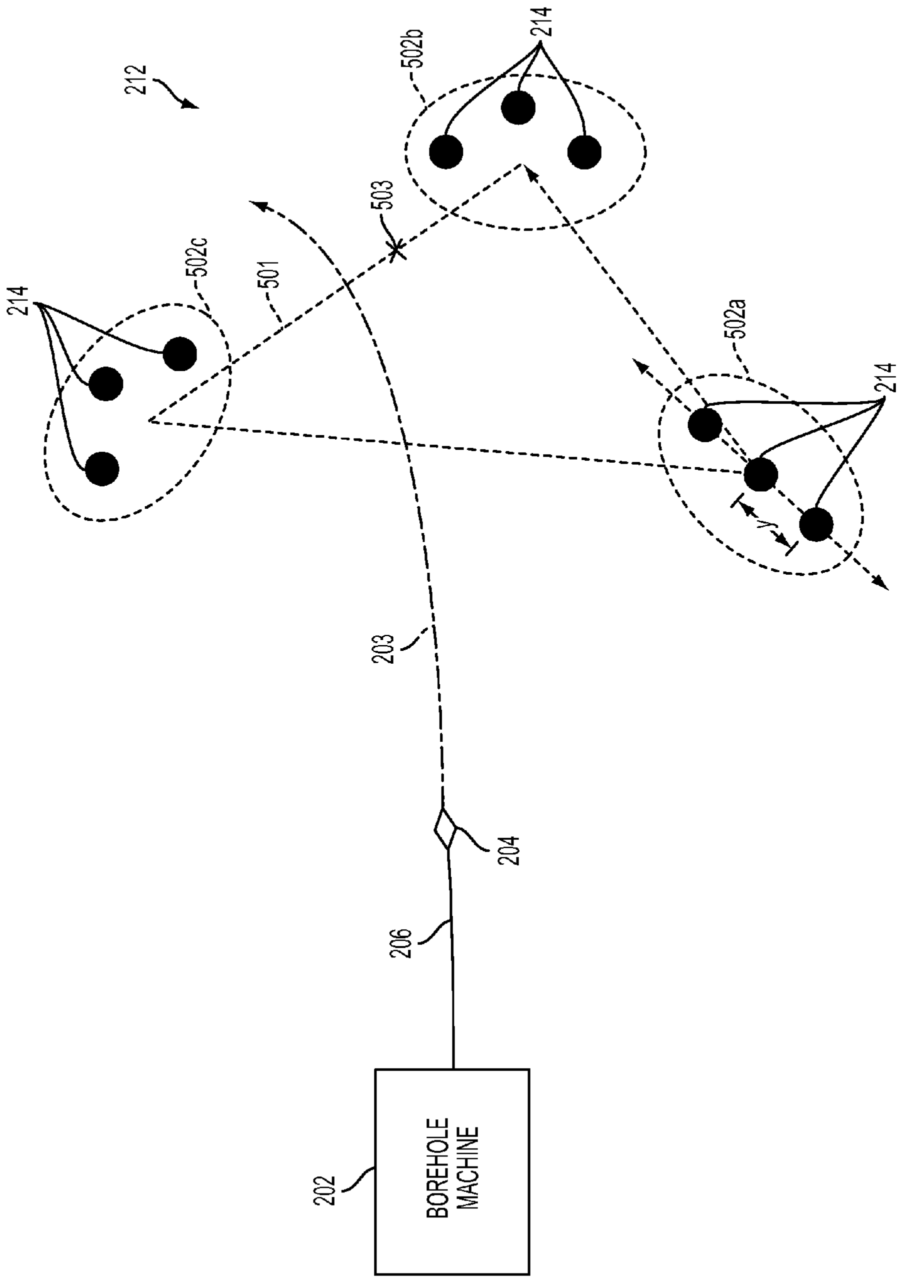

212
214
502b
503
501
502c
214
502a
214
y
203
204
206
202
BOREHOLE MACHINE

FIG. 5

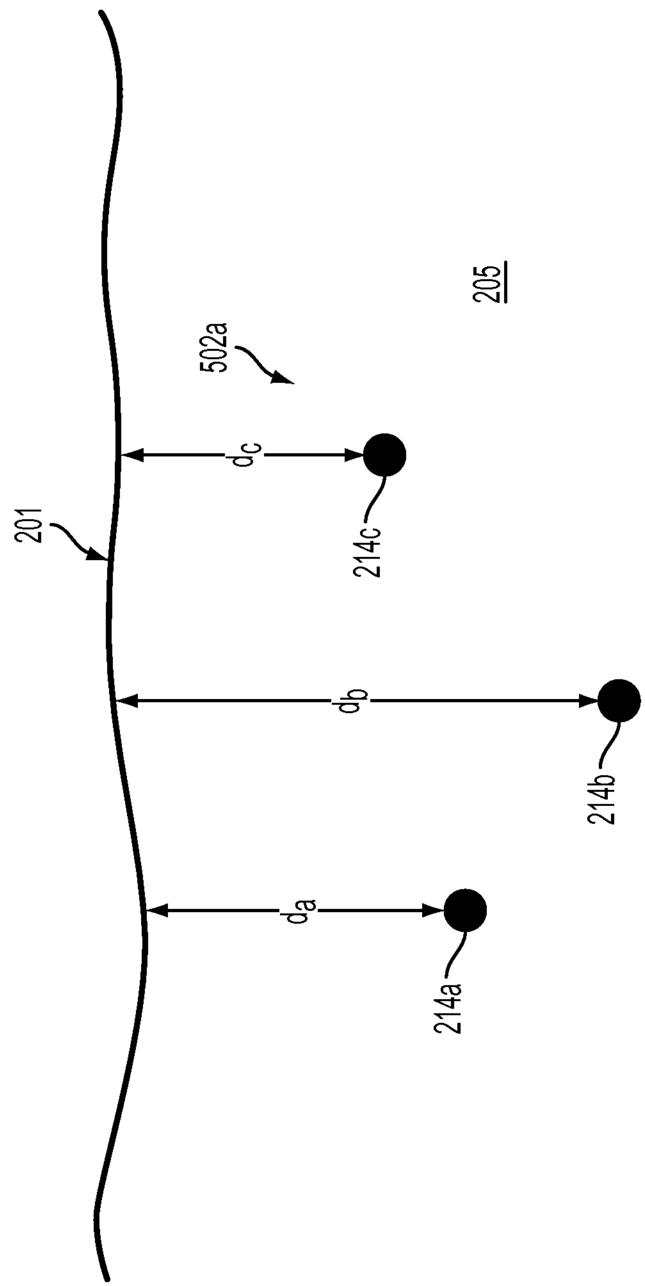


FIG. 6

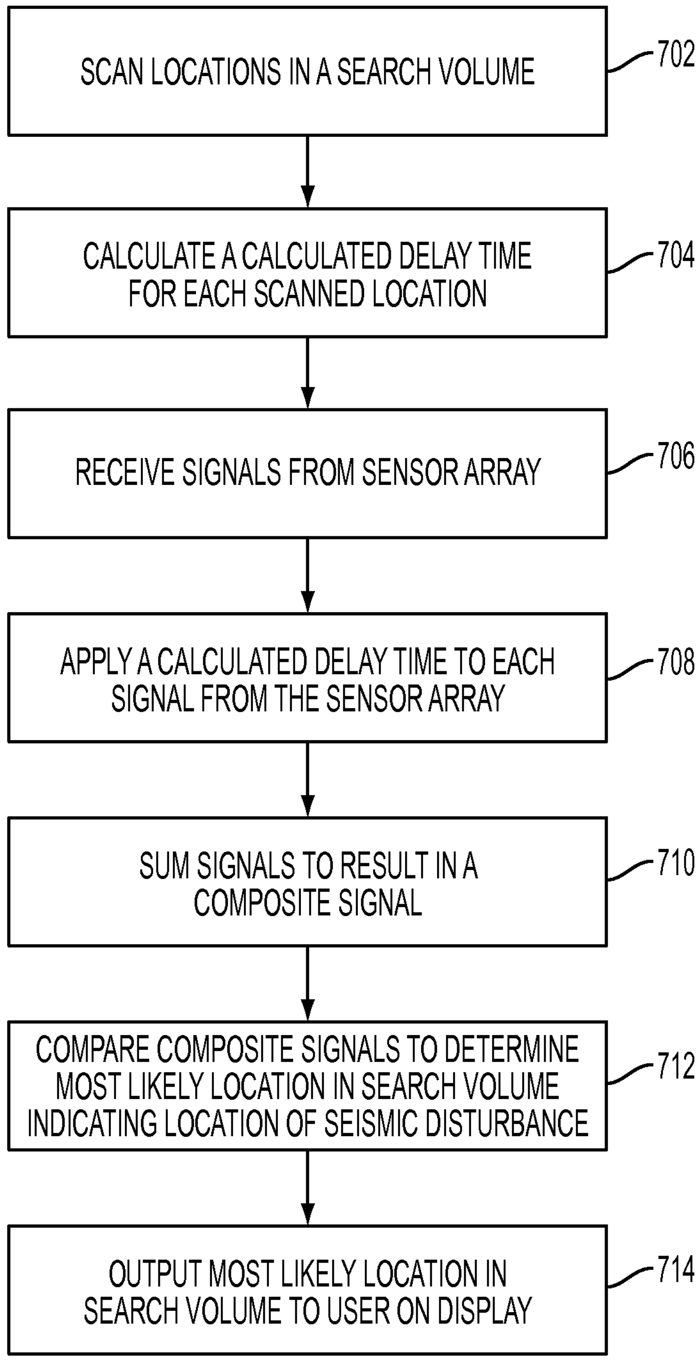

SCAN LOCATIONS IN A SEARCH VOLUME
702
CALCULATE A CALCULATED DELAY TIME FOR EACH SCANNED LOCATION
704
RECEIVE SIGNALS FROM SENSOR ARRAY
706
APPLY A CALCULATED DELAY TIME TO EACH SIGNAL FROM THE SENSOR ARRAY
708
SUM SIGNALS TO RESULT IN A COMPOSITE SIGNAL
710
COMPARE COMPOSITE SIGNALS TO DETERMINE MOST LIKELY LOCATION IN SEARCH VOLUME INDICATING LOCATION OF SEISMIC DISTURBANCE
712
OUTPUT MOST LIKELY LOCATION IN SEARCH VOLUME TO USER ON DISPLAY
714

FIG. 7

SEISMIC NAVIGATION

BACKGROUND

The present invention relates to seismic navigation, and more specifically, to providing a method and system for navigating the formation of subterranean boreholes.

Boreholes may be formed using, for example, a horizontal borehole machine. In this regard, FIG. **1** illustrates a prior art example of a borehole machine **102** that uses a bit **104** for excavating earth. The path of the bit **104** may be controlled at the surface **101**. Often the bit **104** includes one or more magnetic beacons that, when used in conjunction with a sensor device **106** disposed on the surface **101**, may determine the position of the bit **104** while located in a borehole **103**. Typically, the sensor device **106** is a portable unit that is moved on the surface **101** over the location of the bit **104** to determine the position of the bit **104** below the sensor device **106**. By determining two or more positions of the bit **104**, the path of the bit **104** may be calculated. Once the path of the bit **104** is calculated, the path of the bit **104** may be adjusted if desired such that a borehole is formed that follows a desired path.

SUMMARY

According to one embodiment of the present invention, a sensor array system includes a sensor array comprising a first sensor disposed underground and a second sensor disposed underground, and a processor communicatively coupled to the sensors of the sensor array, the processor operative to receive signals from the sensors of the sensor array indicative of seismic activity, and identify a position of a portion of a borehole machine operative to induce the seismic activity while disposed in an underground borehole.

According to another embodiment of the present invention, a method includes receiving signals in a processor indicative of a seismic activity induced by a portion of a borehole machine, determining a position of the portion of the borehole machine, comparing the position of the portion of the borehole machine and a intended path of the portion of the borehole machine, and outputting data indicative of the difference between the position of the portion of the borehole machine and the intended path of the portion of the borehole machine.

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** illustrates a prior art example of a borehole machine.

FIG. **2** illustrates an exemplary embodiment of a sensor system.

FIG. **3** illustrates an exemplary embodiment of the processing portion of FIG. **2**.

FIG. **4** illustrates an exemplary embodiment of an arrangement of a sensor **214** in a subterranean disposition.

FIG. **5** illustrates a top view schematic of an exemplary arrangement of the sensor array and the borehole machine of FIG. **2**.

FIG. **6** illustrates a side view of a group of sensors of FIG. **5**.

FIG. **7** illustrates a block diagram of an exemplary method for operating the system of FIG. **2**.

DETAILED DESCRIPTION

As discussed above, the prior art system shown in FIG. **1** uses a sensor device **106** that is disposed on the surface **101** above the bit **104**. However, if the area of the surface **101** that is above the bit **104** is inaccessible by personnel operating the sensor device **106**, the path of the bit may not be determined using the prior art system and methods. The embodiments described below provide a method and system for determining a position and path of a bit that forms a subterranean borehole.

FIG. **2** illustrates an exemplary embodiment of a sensor system **200** that is operative to determine a position and path of a bit **204**. In this regard, FIG. **2** shows a borehole machine **202** disposed on the surface **201** of terrain **205**. The borehole machine **202** includes a bit **204** that is driven with a drill pipe **206** to form a borehole **203** by removing earth from the terrain **205** along an intended path illustrated by the arrow **207**. The borehole machine **202** is but one example, and it will be appreciated that any suitable horizontal borehole drilling machine or method may be used in alternate embodiments. The sensor system **200** includes a processing portion **210** that is communicatively connected to a sensor array **212** that includes sensors **214**. The processing portion **210** is shown in further detail in FIG. **3**, and includes a processor **302** that is communicatively connected to a display device **304**, input devices **306** that include, for example the sensors **214** of the sensor array **212**, and a memory portion **308**. Referring back to FIG. **2**, the sensor **214** may include for example, a geophone, a hydrophone, or other types of sensors that are disposed below the surface **201** and are operative to detect seismic activity. The sensor array **212** may include either type of sensors **214** (e.g., geophone or hydrophone sensors) or a combination of both types of sensors. In operation, the sensor array **212** is operative to detect seismic activity caused by the operation of the borehole machine **202**, and determine a location of the bit **204** relative to the sensor array **212** as a function of the detected seismic activity. Once the location of the bit **204** relative to the sensor array **212** is determined, the location of the bit **204** relative to the intended path **207** of the bit **204** may be determined. If the bit **204** is not following the intended path **207** recommendations for changing the path of the bit **204** to approach the intended path **207** are sent the borehole machine **202**. In this regard, the borehole machine **202** may be controlled by operators who receive the recommendations verbally, or via a communications link. Alternate embodiments include a control system of the borehole machine **202** that receives feedback signals from the processing portion **210** indicative of the position of the bit **204** relative to the intended path **207**. The feedback signals are used to control the path of the bit **204** relative to the intended path **207** in, for example, a substantially closed loop control system.

In this regard, the sensor array **212** may detect seismic activity caused by the formation of the borehole (i.e., the drill bit **204** moving earth to form the borehole), alternatively, the drill pipe **206** may be manipulated with, for example, a vibratory mechanism to induce seismic activity that emanates from the proximity of the bit and is detected by the sensor array **212**.

FIG. **4** illustrates an exemplary embodiment of an arrangement of a sensor **214** in a subterranean (underground) disposition. A sensor borehole **401** is formed at a desired depth. The depth of the sensor borehole **401** may be selected based in part on the depth of the planned path of the bit **204** (of FIG. **2**). A grout material **402** is disposed in the sensor borehole **401**. The grout material **402** may include, for example, a fluid material that will solidify or partially solidify over time, such as, for example, a concrete type material. The properties of the grout material **402** may be selected such that when solidified the grout material **402** will exhibit similar characteristics as the surrounding earth **403**. A container **404** such as, for example, a cylindrical pipe having a closed end is placed in the grout material **402**. The container **404** has a length that is greater than the depth of the grout material **402** in the sensor borehole **401** such that the open end of the container **404** remains exposed, and the grout material **402** does not enter the inner cavity of the container **404**. Once the grout material **402** solidifies or partially solidifies, the sensor **214** is lowered into the sensor borehole **401** and into the container **404** to a desired depth d. The container **404** is filled with a fluid **406**. The grout **402** and the fluid **406** that surround the sensor **214** improve the performance of the sensor **214** by improving the transmission of seismic indications (i.e., changes in pressure, or movement) to the sensor **214**. The embodiment illustrated in FIG. **4** allows the use of grout **402** and the removal of the sensor **214** from the sensor borehole **401** if desired. If recovery of the sensor **214** is not desired, in alternate embodiments, the sensor **214** may be immersed in the grout material **402** without the use of the container **404** and the liquid **406**.

FIG. **5** illustrates a top view schematic of an exemplary arrangement of the sensor array **212** and the borehole machine **202**. The sensor array **212** of the illustrated embodiment includes three groups **502** of sensors **214**. The groups **502** are arranged in a pattern. In the illustrated embodiment the pattern is triangular; however, alternate embodiments may include any suitable alternate pattern or number of groups. In the illustrated embodiment, each group **502** includes three sensors **214**, however alternate embodiments may include any number of sensors **214** including a single sensor **214** or multiple sensors **214**. The sensors **214** may be arranged in any desired configuration in a group **502**. For example, the groups **502***b* and **502***c* include sensors **214** arranged in a triangular configuration, while the sensors **214** arranged in the group **502***a* are arranged in a linear configuration. The spacing of each sensor **214** in a group is determined partially by the expected wavelengths of the seismic indications that are sensed by the array **212**. The spacing of each group **502** relative to each other is determined by the desired path **203** of the bit **204**, and the sensitivity of the sensors **214** in the array. In the illustrated embodiment, the distance between each of the sensors **214** in a particular group **502** is less than the distance between the groups of sensors **502** (e.g., the distance x between sensors **212** in group **502***a* and sensors **212** in group **502***b* is greater than the distance y between the individual sensors **212** in the group **502***a*). The sensitivity of the sensors **214** in the array **212** is partially determined by the type of sensor **214** used, and the type of earth the sensors **214** in which the sensors **214** are disposed. The illustrated embodiment of FIG. **5** is but one example, and other embodiments may include as few as two or three individual sensors **214** that define the array **212**.

In this regard, an exemplary array **212** may include two groups (e.g., **502***a* and **502***b*) that are arranged adjacent to the intended path **203**. Alternatively, the array **212** may include two groups (e.g., **502***b* and **502***c*) that are arranged such that a plane defined by a plumb line **503** and a line between the two groups **501** intersecting the plumb line.

FIG. **6** illustrates a side view of the group **502***a*. In this regard, the sensors **214***a*, **214***b*, and **214***c* are disposed at depths d_a, d_b, and d_c from the surface **201** respectively. The deposition of the sensors **214** at different depths as opposed to similar depths improves the resolution of the array **214**. This improvement is realized by the ability to resolve an otherwise inherent depth ambiguity of the bit **204** relative the depth of the sensors **214** in the array **212**. Seismic disturbances originating from locations some distance above and below the sensor array **212** depth will arrive at the sensor **214** locations with identical propagation delays. If all sensors **214** are at substantially the same depth, then it is difficult to determine if a seismic disturbance originated from some distance above or below the array **214** unless additional information is considered. This additional information may include previous drill bit **204** location estimates or the calculate results of a air-ground surface reflection model. If, on the other hand, sensors **214** are placed at various depths then seismic disturbance signals with arrive at one or more before arriving at another.

FIG. **7** illustrates a block diagram of an exemplary method for operating the system **200** (of FIG. **2**). In this regard, referring to FIG. **7**, the processor repeatedly scans through locations within a desired search volume in block **702**. In block **704**, for each location a calculated delay time is calculated, representing the time it would take for a "sound" from that location to arrive at each sensor **214** in the array **212**. This set of delays—one per sensor—is applied to the electrical or digital signals received from each of the sensors **214** in blocks **706** and **708**. This creates a set of signals delayed relative to each other. In block **710**, the signals are summed together resulting in one composite signal. After repeating this delay-and-sum algorithm once for each location considered within the search volume, the composite signals may be compared to determine the most likely location within the searched volume responsible for the seismic disturbance sound. (I.e., the location of the bit **204**.) The comparison may consider simple features of the composite signals, for example which has the highest amplitude. Alternately, it may consider particular characteristics of the composite signals, for example which composite signal best matches an exemplary "sound-print" of a drill operating in a particular type of soil. In any case, the comparison results in an estimated drill bit **204** location for the time period during which the signals were collected. In block **714**, the most likely location in the search volume indicating the location of the source of the seismic disturbance is output to a user on the display device **304** (of FIG. **3**).

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one more other features, integers, steps, operations, element components, and/or groups thereof.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, Calcmaterial, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiment was chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated

The flow diagrams depicted herein are just one example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

While the preferred embodiment to the invention had been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

What is claimed is:

1. A sensor array system comprising:

a sensor array comprising first, second and third distinct groups of multiple proximal sensors disposed underground,

at least one of the first, second and third distinct groups of multiple proximal sensors being arranged in a first configuration of sensors and at least another one of the first, second and third distinct groups of multiple proximal sensors being arranged in a second configuration of sensors, which is geometrically distinct from the first configuration of sensors; and

a processor communicatively coupled to each sensor of each of the distinct groups of the multiple proximal sensors of the sensor array, the processor operative to receive signals from the sensors indicative of seismic activity, and to identify a position of a portion of a borehole machine operative to induce the seismic activity while disposed in an underground borehole,

wherein each sensor in each of the first, second and third distinct group of multiple proximal sensors is respectively disposed in a single, unique borehole.

2. The system of claim **1**, wherein the portion of the borehole machine includes a bit disposed in the underground borehole.

3. The system of claim **1**, wherein the processor is operative to determine the position of the portion of the borehole machine relative to an intended path of the portion of the borehole machine and output data indicative of the position of the portion of the borehole machine relative to the intended path of the portion of the borehole machine.

4. The system of claim **3**, wherein the data is output to a display.

5. The system of claim **3**, wherein the data is output to a controller operative to control the borehole machine.

6. The system of claim **3**, wherein the intended path of the portion of the borehole machine intersects a plane that contains a line defined by two of the first, second and third distinct groups of multiple proximal sensors.

7. The system of claim **1**, wherein at least one of the first, second and third distinct groups of multiple proximal sensors comprises sensors arranged at dissimilar underground depths.

8. The system of claim **1**, wherein at least one of the first, second and third distinct groups of multiple proximal sensors comprises first, second and third proximal sensors.

9. The system of claim **1**, wherein the first configuration of sensors is a triangular pattern of multiple proximal sensors of varying depth and the second configuration of sensors is a linear pattern of multiple proximal sensors of varying depth.

10. The system of claim **1**, wherein each of the first, second and third distinct groups of multiple proximal sensors respectively comprises first, second and third sensors that are closer to each other than to any sensors of any other group.

11. The system of claim **1**, wherein the first sensor includes a geophone and the second sensor includes a geophone.

12. The system of claim **1**, wherein the first sensor includes a hydrophone and the second sensor includes a hydrophone.

13. The system of claim **1**, wherein the first sensor includes a hydrophone and the second sensor includes a geophone.

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